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GAIPOS-3250; No. of Pages 3

ARTICLE IN PRESS

Gait & Posture xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Short Communication

The role of lower extremity joint powers in successful stair ambulation

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ARTICLE INFO

Article history:
Received 30 June 2010
Received in revised form 9 March 2011
Accepted 11 March 2011

Keywords:
Stairs
Plantarflexors
Ankle power
Center of mass

ABSTRACT

Ascending stairs is an important functional activity that is affected by lower extremity pathology including amputation. Although several studies have demonstrated stair ascent is more challenging than level ground walking, our understanding of the mechanics remains limited. The purpose of this study was to determine the association between lower extremity joint power generation and vertical COM acceleration (COM_A) during stair ascent. Twenty-two healthy individuals underwent a biomechanical gait assessment while walking up a 16-step instrumented staircase. The association between the peak joint powers and peak COM_A during stance were assessed with respect to timing and magnitude. With respect to timing, peak ankle joint power was highly correlated with peak COM_A ($R^2 = 0.93$), while peak knee and hip joint powers demonstrated limited association with COM_A ($R^2 = 0.41$ and 0.08, respectively). Only the magnitude of peak ankle power was associated with peak COM_A ($R^2 = 0.3$).

Significant temporal and magnitude associations between peak ankle joint power and peak COM_A suggest ankle power is a key contributor to COM_A. Although peak knee joint power and COM_A are temporally associated, the association is weaker and the occurrence of peak joint knee power is nearly 10% after peak COM_A, suggesting knee joint power plays a lesser role in COM_A. These combined findings indicate the role of trail limb ankle plantarflexors should be recognized in the stair ascent cycle definition and demonstrate the potential importance of a power generated by the ankle plantarflexors to normalize stair ascent performance following lower extremity amputation.

Published by Elsevier B.V.

1. Introduction

Ascending stairs is a common and important functional activity that is affected by a range of conditions including lower extremity amputation [1]. Although several studies have demonstrated ascending stairs is more challenging than level ground walking, and performance is limited by pathology, our understanding of stair ascent mechanics remains limited [1–4].

As with early definitions of the gait cycle for level ground walking, the stair ascent (SA) gait cycle is subdivided into phases based on the current understanding of the role of the limb in successful activity performance. The stair ascent cycle definition first proposed by McFadyen et al. [5] includes the actions of weight acceptance, pull-up, forward continuance, foot clearance, and foot placement and emphasized the role of the leading limb knee extensors in pulling the individual up the step [5]. This framework was modified by Zachazewski et al. [6] by replacing the pull-up phase with the term vertical thrust. Although the role of the lead limb in successful stair ascent has been emphasized, the relative contributions of lower extremity joint powers, to include relative timing and magnitude have not been previously explored.

The aim of this study was to investigate the role of lower extremity musculature on elevation of the body, by assessing the temporal and magnitude relationships between vertical COM acceleration (COM_A) and lower extremity joint powers. We hypothesized the trail limb ankle plantarflexors play an important role given their recognized importance in the performance of other ambulatory activities [7].

2. Methods

Twenty-two healthy individuals (13 male, 9 female) between the ages 18 and 45 with no current pain or history of major lower extremity injury volunteered to participate in this study. Subjects were on average 21 ± 4 years old with a mean body mass and height of 74 ± 15 kg and 1.71 ± 0.08 m, respectively. Following written informed consent, all subjects participated in a biomechanical gait assessment during stair ascent walking. A total of 55 markers were used to track whole body motion while subjects walked up a 16-step instrumented staircase (AMTI, Inc., Watertown, MA) at a controlled cadence of 80 steps per minute (Fig. 1). Kinematic data were collected at 120 Hz using a 26 camera optoelectronic motion capture system (Motion Analysis Corp., Santa Rosa, CA).

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0966-6362/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.gaitpost.2011.03.015

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **11 MAR 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **The Role Of Lower Extremity Joint Powers In Successful Stair Ambulation**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Brooke Army Medical Center,Military PerformanceLaboratory,DepartmentofOrthopedicsandRehabilitation,,Fort Sam Houston,TX,78234**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Article in Press,11 March 2011

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**3**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Fig. 1. Photograph of instrumented staircase.

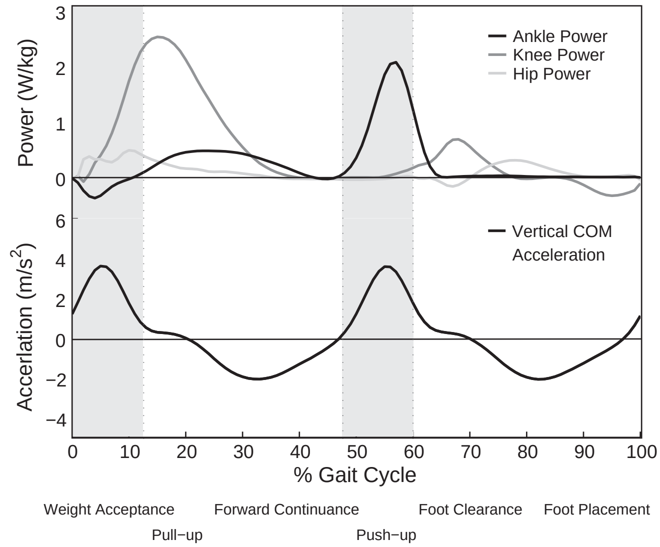

Fig. 2. Mean joint powers and vertical center of mass acceleration for all subjects. Text at the bottom of the figure illustrates stair ascent gait cycle phases including the proposed push-up phase during late stance. The vertical grey bands represent the double limb support phase of the gait cycle. The contribution of peak knee and hip powers during early stance were assessed in relation to the first peak in vertical center of mass acceleration, while the peak ankle power at the end of stance was assessed relative to the second peak in vertical center of mass acceleration.

Segmental markers and 20 anatomical landmarks were used to create a 13 segment model consisting of two feet, two shanks, two thighs, two arms, two forearms, pelvis, trunk, and head based on International Society of Biomechanics standards. Segmental masses were assigned based on total body weight and Dempster's anthropometric data [8]. Kinetic data were collected at 1200 Hz using an interlaced staircase design on two force plates (AMTI, Inc., Watertown, MA) similar to that described by Della Croce and Bonato [9]. Kinetics from steps five and seven were recorded using the first force plate and steps six and eight were recorded using the second force plate. Five trials with unobstructed marker data and clean foot contact were recorded for each subject. Marker and analog data collected using EVaRT software (Motion Analysis Corp., Santa Rosa, CA) were exported and analyzed using Visual3D (C-Motion Inc., Germantown, MD) and Matlab (The Mathworks, Natick, MA) software. Whole body center of mass was calculated as the weighted average of each segment. Center of mass acceleration was calculated as the second derivative of the center of mass position using a 3-point difference formula. Calculated joint powers and vertical COM acceleration (COM_A) were normalized to 100% of SA gait cycle.

A Pearson product moment correlation coefficient was used to determine the association between the timing of peak joint powers and peak COM_A, and between the magnitude values for peak joint powers and peak COM_A.

3. Results

Fig. 2 displays the mean lower extremity joint powers and COM_A during stair ascent for all subjects. The center of mass accelerates vertically twice during the SA gait cycle with peaks at $6 \pm 1\%$ and $56 \pm 1\%$ of the SA gait cycle. During early stance, the leg acts as the lead limb and generates positive power at the knee ($15 \pm 2\%$ cycle) and hip ($8 \pm 4\%$ cycle), which contributes to the first peak COM_A. During late stance, the leg acts as the trail limb and generates power at the ankle ($57 \pm 1\%$ cycle), which contributes to the second peak COM_A.

The timing of peak ankle joint power and peak COM_A (Fig. 3A) during late stance are significantly correlated ($R^2 = 0.93$, $p < 0.01$). The timing of peak knee joint power and peak COM_A (Fig. 3B) during early stance demonstrated a R^2 value lower than observed for ankle joint power ($R^2 = 0.41$, $p < 0.01$). The relationship between hip joint power timing and peak COM_A (Fig. 3C) timing during early stance was not significantly correlated ($R^2 = 0.08$, $p = 0.21$).

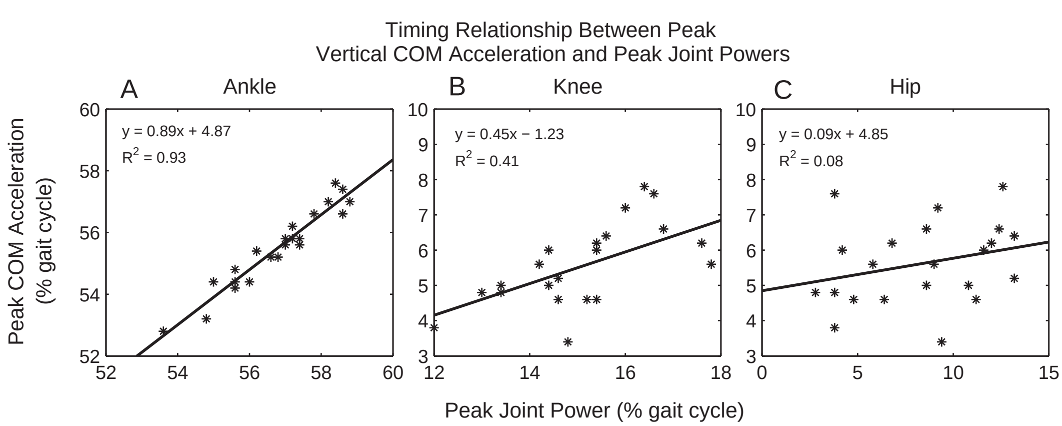

Fig. 3. The relationship between the timing of peak ankle joint power and vertical center of mass acceleration (A), the relationship between the timing of peak knee joint power and vertical center of mass acceleration (B), and the relationship between the timing of peak hip joint power and vertical center of mass acceleration (C).

Please cite this article in press as: Wilken JM, et al. The role of lower extremity joint powers in successful stair ambulation. Gait Posture (2011), doi:10.1016/j.gaitpost.2011.03.015

The magnitude of peak ankle joint power and peak COM_A were significantly associated with an R^2 value of 0.3 ($p < 0.01$). The peak knee and hip joint power magnitude were not associated with peak vertical COM_A magnitude ($R^2 < 0.13$, $p < 0.16$).

4. Discussion

The current investigation was conducted to better understand the role of lower extremity joint powers in successful stair ascent. The results of this study suggest the ankle plantarflexors contribute substantially to vertical acceleration of the body during stair ascent. Peak ankle power is similar in timing and relative magnitude to peak COM_A. Although peak ankle and knee joint power are both temporally associated with COM_A, peak ankle joint power and peak COM_A events occur within 1% of SA gait cycle whereas peak knee power occurs 9% of SA gait cycle after peak COM_A. During the first half of stance there is significant positive power generated at the knee, but the peak occurs after peak COM_A, and a majority of knee joint power occurs while vertical COM_A is near zero. It is possible ankle joint power is used to accelerate the COM_A vertically, while subsequent power production at the knee maintains vertical motion of the body during the remainder of the pull-up or vertical thrust phase of the stair ascent cycle.

The results of the current study suggest the stair ascent cycle definition first proposed by McFadyen et al. [5], which includes the actions of weight acceptance, pull-up, forward continuance, foot clearance, and foot placement should be revised. We suggest a "push-up" phase be included after forward continuance, during the period of double limb support, to recognize the role of the plantarflexors. An important role of the ankle plantarflexors in successful stair ambulation is consistent with recent musculoskeletal computer simulations suggesting ankle push-off is a key contributor to upward acceleration of the body during normal level ground walking [7,10].

5. Conclusion

Although limitations of inferring the effects of joint powers on distant segments are well documented [10], the findings of the current study suggest the importance of ankle plantarflexors in successful stair ascent and warrant further investigation. An improved understanding of the mechanics of stair ascent has potential implications for the development and testing of powered prosthetic and orthotic devices designed to facilitate the normalization of stair performance through the restoration of ankle power.

Acknowledgement

Support provided by the Military Amputee Research Program (to JMW).

Conflict of interest statement

The authors have no conflicts of interest to report.

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